Modified incremental conductance MPPT algorithm to mitigate inaccurate responses under fast-changing solar irradiation level

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Abstract

During the increment of solar irradiation, the conventional incremental conductance algorithm responds inaccurately at the first step change in the converter duty cycle. This paper presents the conventional algorithm confusion and proposes a modified incremental conductance algorithm that responds accurately when the solar irradiation level increases. Moreover, the proposed algorithm shows zero oscillation in the power of the solar module after the maximum power point (MPP) is tracked. MATLAB simulation is carried out with the modified incremental conductance algorithm under a fast-changing solar irradiation level. Results of the modified, conventional and variable step size incremental conductance algorithms are compared. Finally, the hardware implementation, consisting of a single-ended primary-inductor converter (SEPIC) and a PIC controller, is applied as the maximum power point tracking (MPPT) controller. The simulation and experimental works showed that the proposed algorithm performs accurately and faster during the increment of solar irradiation level.

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Keywords: MPPT; Incremental conductance; Photovoltaic (PV) system; SEPIC converter; Fast changing solar irradiation

1. Introduction

Electricity generation using solar energy has gained increasing popularity in recent years (Mekhilef et al., 2011, 2012). However, electricity generated by photovoltaic (PV) panels is an unstable energy source because of its firm dependence on factors such as solar irradiation level and surrounding temperature. Therefore, maximum power point tracking (MPPT) controller is needed to improve the efficiency of the PV system by ensuring that the PV module continuously supplies maximum power despite changes in weather conditions (de Cesare et al., 2006; Houssamo et al., 2010).

To ensure the high efficiency of the PV system, numerous MPPT algorithms have been developed, such as Fractional Open-Circuit Voltage (FOCV), Fractional Short-Circuit Current (FSCC), Fuzzy Logic, Neural Network, Perturbation and Observation (P&O), and Incremental Conductance (Reza Reisi et al., 2013; Gounden et al., 2009; Chaouachi et al., 2010; Altas and Sharaf, 2008; Faranda et al., 2008; de Brito et al., 2011; Ishaque et al., 2012). The simplest algorithms are FOCV and FSCC, which use the linearity of open-circuit voltage or short-circuit current to the maximum power point (MPP) voltage or current. However, these algorithms require intermittent disconnection of the PV module to obtain the open-circuit voltage or short-circuit current. Thus, overall efficiency of the PV system is lower because of the power losses during the disconnection (Qiang et al.,...
Alternatively, Fuzzy Logic or Neural Network is chosen to obtain an accurate MPPT algorithm because of their ability to handle the non-linearity and dispensability of an accurate mathematical model, but these algorithms highly depend on user experience on the PV module characteristics (Gounden et al., 2009; Chauouchi et al., 2010; Altas and Sharaf, 2008; Liu et al., 2013; Whei-Min et al., 2011). The PV module’s characteristics change along with time because of degradation. Therefore, the algorithm parameters need to be updated.

Among the aforementioned algorithms, P&O and incremental conductance are frequently used. These two algorithms work in accordance with the power against voltage (P–V) curve of the PV module. Both algorithms tune the DC–DC converter duty cycle in the PV system to ensure that the latter operates at the MPP. For P&O, steady-state oscillation occurs after the MPP is reached because the perturbation continuously changes in both directions to maintain the MPP (Weidong and Dunford, 2004; Weidong et al., 2007; Ferreira et al., 2007; Ferreira et al., 2005; Abdelsalam et al., 2011). Steady-state oscillation causes system power losses. For incremental conductance, the slope of the P–V curve is used for MPPT. The conventional incremental conductance algorithm determines the gradient of the P–V curve. In addition, the duty cycle of the converter is tuned in fixed step size until the peak (gradient is equal to zero) of the P–V curve is reached. However, the algorithm speed is slow when fixed step size is used. Therefore, Rahman et al. (2013) and Fangrui et al. (2008) introduced the variable step size in MPPT. In the algorithm, the fixed step size is multiplied with the slope of the P–V curve. Thus, the duty cycle step size becomes smaller when the PV system operates near to the MPP (peak of the P–V curve). Meanwhile, the step size is larger and possesses faster tracking speed when the PV system operates far from the MPP. Theoretically, when the peak of the P–V curve is found, no further perturbation of duty cycle or no oscillation in the power of the PV module (Qiang et al., 2011; Rahman et al., 2013; Fangrui et al., 2008; Kakosimos and Kladas, 2011) occurs. However, during implementation, the zero value is rarely obtained on the slope of the P–V curve because of the truncation error in digital processing. Conventional and variable step size incremental conductance algorithms are also unable to respond accurately at the first step change in the duty cycle of the converter after the increase in solar irradiation level (Zbeeb et al., 2009). Therefore, the present paper introduces new tracking steps to identify the changes in solar irradiation level. The variations in current (dI) and voltage (dV) of the PV module are used to track the increase in solar irradiation instead of the slope (dP/dV) of the P–V curve. The proposed algorithm can respond accurately during the changes in solar irradiation level. Moreover, a small permitted error is used in the proposed algorithm to ensure that no steady-state oscillation occurs. The results of both simulation and hardware implementation are provided. The results of the proposed algorithm are compared with those of the conventional algorithm. The comparison reveals that the proposed algorithm performs better by eliminating the steady-state oscillation and by responding faster and accurately to the variation in solar irradiation level. Fig. 1 shows the block diagram of the PV system.

### 1.1. PV module characteristic

PV module is a current source that comprises a number of solar cells connected in series or parallel to generate electrical energy when there is sunlight. Solar cell is a type of semiconductor that produces electricity when sunlight is emitted onto it (Bennett et al., 2012). To understand solar cell characteristics, mathematical models have been developed. Few types of models have been created, such as single-diode and two-diode models (Bennett et al., 2012; Ishaque and Salam, 2011; Ishaque et al., 2011; Gonzalez-Longatt, 2005). For simplicity, some models ignore the shunt resistance $R_{sh}$, which is normally very large and can be considered as an open circuit. In this paper, single-diode model from Gonzalez-Longatt (2005) is chosen to model the solar cell. The mathematical expression for the equivalent electric circuit used in the model is shown below:

$$I = n_p I_{sc} - n_p I_o \left\{ \exp\left[\frac{q(V/n_s + R_s I)}{nkT_s}\right] - 1 \right\}$$  \hspace{1cm} (1)

where $V$ is the output voltage of PV module, $I$ the output current of PV module, $R_s$ the series resistance of cell, $q$ the electron charge, $I_{sc}$ the light-generated current, $k$ the Boltzmann constant, $T_s$ the temperature (K), $n$ the diode ideality factor, $n_s$ the number of PV cells connected in series, $n_p$ the number of PV cells connected in parallel, and $I_o$ the reverse saturation current.

As shown in Gonzalez-Longatt (2005), $I_{sc}$ is affected by temperature and solar irradiation while $I_o$ is only affected by temperature. The PV module model is generated using Eq. (1) and the Newton–Raphson method in MATLAB.

The maximum power available from the PV module depends on the surrounding temperature and solar irradiation level. Fig. 2 shows the two main characteristic curves, namely, current against voltage curve ($I–V$ curve) and $P–V$ curve. These curves are used to investigate the effect of temperature and solar irradiation level on the PV module. When a load is connected to the PV module, a load line is imposed on the $I–V$ curve. The voltage and current of

![Fig. 1. Block diagram of the PV system.](image)
the PV module are at the point where the load line intersects with the $I$–$V$ curve. Then, the power is simply the multiplication of the current and voltage at the intersection point. The load line position on the $I$–$V$ curve depends on the impedance of the load (Coelho et al., 2009; Ying-Tung and China-Hong, 2002). Therefore, a DC–DC converter is needed between the PV module and load.

The duty cycle of the DC–DC converter is tuned to ensure that the load line always intersects with the $I$–$V$ curve at the MPP (Fig. 2). MPPT algorithm is used to ensure that the PV module constantly operates at the MPP, regardless of the intensity of sunlight, surrounding temperature, and load resistance.

2. Conventional and variable step size incremental conductance algorithm

Incremental conductance algorithm detects the slope of the $P$–$V$ curve. The MPP is tracked by searching the peak of the $I$–$V$ curve. This algorithm uses the instantaneous conductance $\frac{dI}{dV}$ and the incremental conductance $\frac{dP}{dV}$ for MPPT. Using these two values, the algorithm determines the location of the operating point of the PV module in the $P$–$V$ curve. Eq. (2) shows that the PV module operates at the MPP. Meanwhile, Eq. (3) shows that the PV module operates at the left side of the MPP, whereas Eq. (4) shows that the PV module operates at the right side of the MPP in the $P$–$V$ curve (Qiang et al., 2011; Fangrui et al., 2008; Safari and Mekhilef, 2011; Zhou et al., 2008; Bo-Chiau and Chun-Liang, 2011).

$$\frac{dI}{dV} = - \frac{I}{V}$$

(2)

$$\frac{dI}{dV} > - \frac{I}{V}$$

(3)

$$\frac{dI}{dV} < - \frac{I}{V}$$

(4)

The equations above are obtained from the concept where the slope of the $P$–$V$ curve at MPP is equal to zero, as shown in Eq. (5):

$$\frac{dP}{dV} = 0$$

(5)

By rewriting Eq. (5), the following equations are obtained:

$$\frac{dP}{dV} = I \frac{dV}{dV} + V \frac{dI}{dV}$$

(6)

$$\frac{dP}{dV} = I + V \frac{dI}{dV}$$

(7)

$$I + V \frac{dI}{dV} = 0$$

(8)

In the conventional incremental conductance algorithm, Eq. (8) is used to detect the MPP and flowchart of the algorithm is as shown in Fig. 3(a). The voltage and current of the PV module are sensed by the MPPT controller. If Eq. (3) is satisfied, the duty cycle of the converter needs to be decreased, and vice versa if Eq. (4) is satisfied. No change on the duty cycle occurs if Eq. (8) is satisfied.

The variable step size incremental conductance algorithm proposed in Fangrui et al. (2008) is able to increase the tracking speed of the MPPT controller. The flow chart of the algorithm is shown in Fig. 3(b). The sequences in the algorithm are mostly similar to the conventional incremental conductance and the only difference is the step size calculation. Eq. (9) is used in the variable step size algorithm to vary the duty cycle step size where $N$ is the scaling factor.

$$\text{Step} = N \cdot \text{abs}(\frac{dP}{dV})$$

(9)

2.1. Weakness of conventional and variable step size incremental conductance

Incremental conductance algorithm uses the slope of the $P$–$V$ curve to detect the MPP. If the algorithm finds that the operating point is at the peak of the $P$–$V$ curve (slope equals to zero) and if Eq. (5) is satisfied, then the duty cycle of the DC–DC converter is fixed and no oscillation during this stage occurs until changes in the slope arise. However, in real life, the zero slope condition is rarely achieved, as mentioned in Weidong et al. (2007), because of the truncation error of the numerical differentiation.

Apart from steady-state oscillation, the conventional algorithm is confused when the solar irradiation increases. As shown in Fig. 4, when the irradiation is at 0.4 kW/m², the MPPT algorithm adjusts the duty cycle to ensure that the PV system operates at load line 2 and the MPP (point B) is tracked. After some time, the solar irradiation increases, but the duty cycle is maintained at load line 2. Therefore, point G will be found by load line 2 in the $I$–$V$ curve of 1.0 kW/m², corresponding to the power at point C in the $P$–$V$ curve. The conventional incremental conductance algorithm calculates the gradient between points B and C. The result is a positive gradient. In fact, the power found by load line 2 is at point C. The gradient between point C and the MPP (point A) of 1.0 kW/m² has a negative value. Without noticing this error, the conventional incremental conductance algorithm increases the voltage of the PV module. Therefore, an inaccurate first step change is implemented by the conventional algorithm when solar irradiation level changes from low to high.
However, this problem does not occur when the solar irradiation level decreases from high to low. The reason is because from points E to H, or in the P–V curve from points A to D, the gradient is positive. The gradient between points B and D is also positive.

3. Proposed incremental conductance algorithm

The incremental conductance algorithm depends on the slope of the P–V curve, which is affected by the solar irradiation level and load resistance. The algorithm uses the current and voltage of the PV module in the calculation. Therefore, the effect of solar irradiation and load changes on the current and voltage of the PV module must be well considered in the algorithm.

Table 1 shows the summary of changes in the voltage and current of the PV module against the changes in solar irradiation level and load resistance. As shown in Fig. 4, when the PV system operates at load line 2 (point F) and solar irradiation suddenly increases, the operating point of the PV system moves to point G. Therefore, both voltage and current increase. Conversely, when the PV system operates at load line 1 (point E) and solar irradiation suddenly decreases, the operating point of the PV system moves to point H. Thus, both voltage and current decrease.

In the conventional incremental conductance algorithm, these two types of changes are not well considered. Meanwhile, if the PV system operates at load line 1 and load resistance increases, the PV system will operate at load line 2. Therefore, the PV module voltage increases and the PV module current decreases. Alternatively, the voltage decreases and the current increases when the load resistance decreases.

A permitted error is applied to eliminate the steady-state oscillation. Eq. (8) is rewritten as

\[ I + V \frac{dI}{dV} < 0.06 \]

Using the permitted error of 0.06, the steady-state error is approximately 0.7% with a duty cycle step size of 0.005 in the proposed algorithm. In order to select the suitable duty cycle step size for the proposed system, simulation data is collected and the PV module used in the simulation is Kyocera KC85T (the parameters of the PV module are in Table 3). Fig. 5 shows the power of the PV module for three different step size values of 0.001, 0.005, and 0.01 when the duty cycle is varied around the MPP. Table 2 summarizes the characteristics for the three different types of step sizes. All step sizes can track the MPP at approximately 86.37 W. Although the 0.01 step size responds very fast, the power value differs at 1.16 W between two consecutive step changes, which is recognized as the largest among the three step sizes. Thus, the MPPT controller is
and the MPP is reached at $t = 0.2\,\text{s}$. The duty cycle fluctuates between 0.61 and 0.62. Simultaneously, oscillation occurs in the power (69.40–69.78\,W) of the PV module. At $t = 0.716\,\text{s}$, the solar irradiation is increased to 1.0\,kW/m$^2$, but the duty cycle remains at 0.62. Consequently, the power of the PV module increases. At $t = 0.75\,\text{s}$, the MPPT controller is sampled with the conventional incremental conductance algorithm. The duty cycle first step change is confusing and obtains inaccurate responses. Therefore, the power of the PV module is decreased, as shown in Fig. 8(a), point A. Afterward, the algorithm reverts direction and the power of the PV module is increased. At $t = 1.0\,\text{s}$, the MPP is reached for solar irradiation of 1.0\,kW/m$^2$. Oscillation in the power of the PV module (86.04–86.37\,W) occurs again. At $t = 1.44\,\text{s}$, the solar irradiation level decreases to 0.8\,kW/m$^2$, and the conventional incremental conductance algorithm works accurately. Fig. 8(b) shows the results of the variable step size algorithm. When the solar irradiation is set to 0.8\,kW/m$^2$, the MPP is reached at $t = 0.2\,\text{s}$. The duty cycle fluctuates between 0.61 and 0.62. Due to the use of Eq. (9) in the algorithm, the duty cycle changes become smaller as the operating point near to the peak. Therefore, the oscillation in the power (69.35–69.78\,W, point D) of PV module is not precise enough. For the 0.001 step size, the power values are close to one another (shown in Fig. 5) when the duty cycle is varied. Therefore, the MPPT controller response is slow. The 0.005 step size shows that the difference in the power of the PV module is acceptable among the three different step sizes. The controller can respond precisely and rapidly with this duty cycle step size. Therefore, 0.005 is chosen as the step size of the duty cycle in the system. In Table 2, the minimum slope value is used to set the permitted error in Eq. (10). As shown in the table, the minimum slope value for the 0.005 step size is 0.0527. Thus, the permitted error is set to 0.06 to stop the varying of step size with the slope value below this permitted error.

Finally, the proposed algorithm is seen in the flow chart shown in Fig. 6. Initially, a flag value is set to zero. This flag value is used to indicate that the MPP is reached when it is set to 1. If the flag value is zero, the conventional incremental conductance algorithm is implemented with the use of Eq. (10). When the condition in Eq. (10) is reached, the system operates at the MPP. Therefore, the algorithm sets the flag to 1, and then goes into the improved algorithm. In the improved algorithm, the program continues checking the condition of Eq. (10). If the solar irradiation and load resistance remain constant, no variation is made on the duty cycle. When changes occur in either solar irradiation or load, the algorithm sets the flag value to zero and then determines the changes in the voltage and current of the PV module. If the algorithm finds that both the current and voltage increased, then the duty cycle is also increased. Consequently, the incremental conductance algorithm is modified to overcome the inaccurate response during the increase in solar irradiation.

### 4. Results and discussion

#### 4.1. Simulation results

Fig. 7 shows the MATLAB Simulink model of the entire MPPT system, which consists of the PV module model, a single-ended primary-inductor converter (SEPIC), and an MPPT controller. The PV module model is designed based on a Kyocera PV module (KC85T module). Table 3 shows the parameters of the module. The values of the components in the converter are as follows: $C_{\text{in}}$ and $C_{\text{out}} = 3900\,\mu\text{F}$, $L_1 = 125\,\mu\text{H}$, and load $= 10\,\Omega$. The switching frequency of the converter is set to 20\,kHz.

The simulation is conducted to investigate the differences between the three algorithms. In the simulation, the solar irradiation is changed from low to high and then to low again. The duty cycle step size for the converter in conventional and proposed algorithm is 0.005, the scaling factor, N in the variable step size is 0.03 and the sampling time for the MPPT controller is 0.05\,s. Fig. 8(a) shows the simulation results of the conventional incremental conductance algorithm. At the beginning of the simulation, the solar irradiation is set to 0.8\,kW/m$^2$, and the MPP is reached at $t = 0.2\,\text{s}$. The duty cycle fluctuates between 0.61 and 0.62. Simultaneously, oscillation occurs in the power (69.40–69.78\,W) of the PV module. At $t = 0.716\,\text{s}$, the solar irradiation is increased to 1.0\,kW/m$^2$, but the duty cycle remains at 0.62. Consequently, the power of the PV module increases. At $t = 0.75\,\text{s}$, the MPPT controller is sampled with the conventional incremental conductance algorithm. The duty cycle first step change is confusing and obtains inaccurate responses. Therefore, the power of the PV module is decreased, as shown in Fig. 8(a), point A. Afterward, the algorithm reverts direction and the power of the PV module is increased. At $t = 1.0\,\text{s}$, the MPP is reached for solar irradiation of 1.0\,kW/m$^2$. Oscillation in the power of the PV module (86.04–86.37\,W) occurs again. At $t = 1.44\,\text{s}$, the solar irradiation level decreases to 0.8\,kW/m$^2$, and the conventional incremental conductance algorithm works accurately. Fig. 8(b) shows the results of the variable step size algorithm. When the solar irradiation is set to 0.8\,kW/m$^2$, the MPP is reached at $t = 0.2\,\text{s}$. The duty cycle fluctuates between 0.61 and 0.62. Due to the use of Eq. (9) in the algorithm, the duty cycle changes become smaller as the operating point near to the peak. Therefore, the oscillation in the power (69.35–69.78\,W, point D) of PV module is not precise enough. For the 0.001 step size, the power values are close to one another (shown in Fig. 5) when the duty cycle is varied. Therefore, the MPPT controller response is slow. The 0.005 step size shows that the difference in the power of the PV module is acceptable among the three different step sizes. The controller can respond precisely and rapidly with this duty cycle step size. Therefore, 0.005 is chosen as the step size of the duty cycle in the system. In Table 2, the minimum slope value is used to set the permitted error in Eq. (10). As shown in the table, the minimum slope value for the 0.005 step size is 0.0527. Thus, the permitted error is set to 0.06 to stop the varying of step size with the slope value below this permitted error.

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### Table 2
Comparison between three different step size values.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Step size</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.001</td>
</tr>
<tr>
<td>Maximum power</td>
<td>86.375 W</td>
</tr>
<tr>
<td>Minimum slope value</td>
<td>0.0165</td>
</tr>
<tr>
<td>Response time</td>
<td>Slow</td>
</tr>
<tr>
<td>Power different between two consecutive step changes</td>
<td>0.00349 W</td>
</tr>
</tbody>
</table>

### Table 3
Parameters of KC85T PV Module at STC: temperature = 25 °C, insolation = 1000 W/m$^2$.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum power ($P_{\text{max}}$)</td>
<td>87 W</td>
</tr>
<tr>
<td>Voltage at MPP ($V_{\text{mpp}}$)</td>
<td>17.4 V</td>
</tr>
<tr>
<td>Current at MPP ($I_{\text{mpp}}$)</td>
<td>5.02 A</td>
</tr>
<tr>
<td>Open-circuit voltage ($V_{\text{oc}}$)</td>
<td>21.7 V</td>
</tr>
<tr>
<td>Short-circuit current ($I_{\text{sc}}$)</td>
<td>5.34 A</td>
</tr>
</tbody>
</table>

![Fig. 5. PV power for three different step size values at solar irradiation level 1000 W/m$^2$ when the duty cycle varies near the MPP.](image-url)
also found to become smaller along with time. At \( t = 0.716 \) s, the solar irradiation is increased to 1.0 kW/m\(^2\). The same problem faced by the variable step size algorithm as the inaccurate duty cycle changes is applied by the MPPT controller as shown in Fig. 8(b), point C. This is due to the algorithm sequence which similar to the conventional algorithm is used during the variation in solar irradiation. During the steady state condition, the power of PV module is also oscillating (86.24–86.37 W). When the solar irradiation level decreases, the algorithm is able to respond accurately and in fact it has faster response due to the use of variable step size.

Fig. 8(c) shows the simulation results of the proposed incremental conductance algorithm. At \( t = 0.2 \) s, the MPP for 0.8 W/m\(^2\) is reached and the duty cycle is maintained at 0.615. The power of the PV module is maintained at 69.78 W. Thus, the power losses are lower due to the reduction in steady-state oscillation. At \( t = 0.716 \) s, the solar irradiation is increased to 1.0 kW/m\(^2\). Then, at \( t = 0.75 \) s, the proposed algorithm detects the increase in solar irradiation and performs an accurate variation in the duty cycle, as shown in Fig. 8(c), point E. Therefore, the power is increased from the first step until the MPP reached \( t = 0.9 \) s and the power of the PV module is maintained at 86.37 W. The proposed algorithm only needs four steps to reach the MPP. The response of the proposed algorithm on the changes in solar irradiation is faster compared with that of the conventional and variable step size algorithm, which needs six steps and five steps respectively. The proposed algorithm is 0.1 s faster compared with the conventional algorithm during the increase in solar irradiation level. Moreover, the steady-state oscillation is reduced when the permitted error reaches 0.06. Finally, the computational time needed by the proposed algorithm is only 0.1 s faster compared with the conventional algorithm during the increase in solar irradiation level. Moreover, the computational time needed by the proposed algorithm is only 4 instructions more than the conventional algorithm which are (i) initialize the flag value to zero, (ii) check the flag value is equal to one or zero, (iii) clear the flag value if the permitted error is not meet, (iv) check the variation in both the current and voltage of PV modules. The proposed algorithm determines the variation direction in the voltage and current before increasing or decreasing the duty cycle in the next sampling time immediately after the variations in solar irradiation. Meanwhile, the conventional algorithm responds in the next sampling time immediately after the variation in solar irradiation. The use of a microcontroller in the hardware implementation causes the processing time of the steps introduced in the proposed algorithm to be less than the sampling time. Therefore, the proposed algorithm does not have any implementation issue with the microcontroller. Table 4 summarizes the comparison between both algorithms.
4.2. Experimental results

For hardware implementation, both conventional and proposed algorithms are implemented using the PIC controller. The PIC used in the controller is Microchip PIC18F4520 with 40 MHz processing speed. A 10-bit ADC conversion is used to convert the voltage and current of the PV module. Current sensor (LEM LA25-NP) and voltage sensor (LEM LV25-P) are used to sense the voltage and current of the PV module. In the experiment, the components of the SEPIC have the same value as in the simulation. The solar array simulator (SAS) from Agilent (E4360A) is used to generate the output characteristics of a PV array. The Agilent SAS is a DC power source with

Fig. 8. Simulation results: (a) Conventional incremental conductance algorithm. (b) Variable step size algorithm. (c) Proposed incremental conductance algorithm.
Table 4
Comparison between the conventional and proposed incremental conductance algorithms.

<table>
<thead>
<tr>
<th>Evaluated parameters</th>
<th>Conventional algorithm</th>
<th>Variable step size algorithm</th>
<th>Proposed algorithm</th>
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<tr>
<td>Tracking steps during increase in solar irradiation level</td>
<td>6 steps</td>
<td>5 steps</td>
<td>4 steps</td>
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<tr>
<td>Steady-state oscillation</td>
<td>Large</td>
<td>Small</td>
<td>No</td>
</tr>
<tr>
<td>Wrong response during increase in solar irradiation</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Practical implementation</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Fig. 9. Agilent solar array simulator and experimental setup of MPPT system.

Fig. 10. $I-V$ curve and $P-V$ curve from the SAS. (a) Conventional incremental conductance algorithm. (b) Proposed incremental conductance algorithm.

Fig. 11. Experimental results: waveform for PV power, voltage, and current. (a) Conventional incremental conductance algorithm. (b) Proposed incremental conductance algorithm.
600 W output and it is primarily a current source with very low output capacitance and is capable of simulating the \( I-V \) curve of different arrays under various conditions. The desired \( I-V \) curve is programmable over the Ethernet and is conveniently generated within the SAS. Fig. 9 shows the SAS and the experimental setup.

The solar irradiation level in the hardware implementation is varied as in the simulation which is from 0.8 kW/m\(^2\) increased to 1.0 kW/m\(^2\) and then decreased back to 0.8 kW/m\(^2\). The experiment results are similar with the simulation results. For conventional and variable step size algorithm, confusion occurs with the increase in solar irradiation, as shown in Figs. 11(a) and 12(a). Oscillation also occurs in the power of the PV module when the MPP is reached. From the \( P-V \) curve given by the SAS, the oscillation in the power of the PV module is from 85.08 W to 86.3 W and the lowest operating point in the steady state is as shown in Fig. 12(b). The larger oscillation in the variable step size algorithm is due to the operating point does not reach near to the MPP yet. When the MPP is reached, the oscillation become smaller and even without oscillation as shown in Fig. 12(a). The proposed algorithm responds accurately against the increase in solar irradiation level, as shown in Fig. 11(b). In addition, no steady-state oscillation occurs when the MPP is reached. The operating point of the PV module during the steady state is shown in Fig. 10(b), 86.3 W.

To ensure that the algorithm is functioning well, the resistive load is varied. Fig. 13 shows the results. Initially, the resistive load is at 10 Ω, and the MPP is tracked. Next, the resistive load changes to 6.67 Ω at point D. The current of the PV module is increased while the voltage is decreased. The PV module operates at the left side of the \( P-V \) curve. The algorithm decreases the duty cycle of the converter to reach the MPP again. Afterward, the resistive load is switched to 10 Ω at point E, the current of the PV module is decreased, and the voltage of the PV module is increased. The PV module operates at the right side of the \( P-V \) curve. The algorithm increases the duty cycle and reaches MPP again.

5. Conclusion

In this paper, the proposed incremental conductance algorithm was used to track the MPP for PV module under a fast-changing solar irradiation level. The confusion faced by the conventional algorithm was discussed. Modifications were applied on the conventional incremental conductance algorithm to mitigate the inaccurate response. The simulation and experimental results showed that the proposed algorithm responds and tracks the MPP accurately. Subsequently, the proposed algorithm does not show steady-state oscillation, thereby reducing the power losses. In conclusion, the proposed algorithm performs accurately and better than the conventional algorithm.
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